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THE IDENTIFICATION OF BLUE HORIZONTAL-BRANCH STARS IN THE INTEGRATED SPECTRA OF GLOBULAR CLUSTERS[1]

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ABSTRACT

A major uncertainty in the spectroscopic dating of extragalactic globular clusters concerns the degenerate effect that age and horizontal-branch morphology have on the strength of Balmer lines. In this Letter we show that the ratio between the equivalent widths of Hδ_F and Hβ is far more sensitive to horizontal-branch morphology than to age, thus making it possible to break the degeneracy. We show that it is possible to distinguish intermediate-age globular clusters from those whose Balmer lines are strengthened by the presence of blue horizontal-branch stars *purely on the basis of the clusters' integrated spectra*. The degeneracy between age and horizontal-branch morphology can be lifted with Hβ and Hδ_F line strengths from spectra with S/N $\gtrsim$ 30 Å^{-1}, which is typical of current studies of integrated spectroscopy of extragalactic globular clusters.

Subject headings: galaxies: evolution — galaxies: stellar content — globular clusters: general — stars: evolution — stars: horizontal-branch

1. INTRODUCTION

In the last decade, the use of equivalent widths (EWs) of Balmer absorption lines in the integrated spectra of old stellar populations (SPs) has become a standard procedure for estimating their light-weighted mean ages (Worthey 1994). The rationale of the method is to utilize the sensitivity of Balmer lines to the temperature and luminosity of turnoff stars, which depend strongly on the age of a SP. However, a well-known caveat is the existence of old hot stars that may be sufficiently bright and numerous to boost the EWs of Balmer lines, mimicking the signature of young stars in the integrated spectra of old SPs. That is the case of blue horizontal-branch (BHB) stars, which are present in such old systems as Galactic globular clusters (GCs) with a range of metallicities (see Moehler 2001 for a review), the halo and bulge fields (e.g., Kinman et al. 2000), the cores of Local Group galaxies (Brown et al. 1998, 2000; Brown 2004), and old Galactic clusters like NGC 6791 (e.g., Peterson & Green 1998). So far the only way of unequivocally distinguishing between an old SP that hosts BHB stars from a truly young SP is by construction of color-magnitude diagrams (CMDs), which of course can only be achieved for nearby systems within the Local Group.

Theoretical studies (Freitas Pacheco & Barbuy 1995; Lee et al. 2000; Maraston & Thomas 2000) have shown that the impact of BHB stars on the integrated spectra of old SPs can be significant, and in particular it may affect the ages inferred from the EWs of Balmer lines. However, in view of the lingering theoretical uncertainties regarding the morphology of the horizontal branch (HB) and its connection with mass loss on the red giant branch (Catelan 2000), an accurate assessment of the contribution of BHB stars to the integrated optical light of old SPs still depends on the availability of CMDs.

[1] Based on observations collected with the CTIO 4 m Blanco Telescope.

In this Letter we present the first results of an ongoing project to calibrate our SP synthesis models with high-quality integrated spectra of star clusters. While this has already been attempted by a number of groups (Beasley et al. 2002; Schiavon et al. 2002a, 2002b; Puzia et al. 2002; Maraston et al. 2003; Leonardi & Rose 2003), our work benefits from the combination of an homogeneous set of high signal-to-noise ratio (S/N) integrated GC spectra newly collected by our group with the *Hubble Space Telescope* (*HST*) CMDs of several tens of Galactic GCs, most of them reaching the GC turnoff, by Piotto et al. (2002). We demonstrate the ability of well-calibrated models, combined with high-S/N spectra, to single out the contribution of BHB stars to the integrated light of GCs. We use a combination of an Fe-sensitive index and an index composed of the ratio of two Balmer line EWs to uniquely constrain the BHB contribution to the integrated light. This enables us to distinguish, *purely on the basis of their integrated spectra*, truly intermediate-age or young clusters from those that are old, but whose Balmer lines are strengthened by the contaminating light of BHB stars. We envisage a direct application of our method to studies of extragalactic GC systems, where the determination of GC ages and metal abundances can yield insight into the star formation and merger histories of the host galaxies (e.g., Cohen et al. 2003; Larsen et al. 2003; Hempel et al. 2003).

2. OBSERVATIONS

We collected integrated spectra for 40 Galactic GCs with the Ritchey-Chrétien spectrograph on the 4 m Blanco Telescope at Cerro Tololo Inter-American Observatory (CTIO) in 2003 April. We scanned a 5′.5 long slit across the core diameter of each target GC. For the GCs located toward the bulge, on-target exposures were interspersed with raster scans of adjacent sky regions ~5′ away from the GC centers. The instrumental setup consisted of grating KPGL1 with 632 lines mm^{-1} and a Loral CCD with

3k × 1k 15 μm sized pixels. The resulting spectra cover the range 3365–6435 Å with a 2.8 Å FWHM resolution. The exposure times were scaled to yield spectra with S/N $\gtrsim$ 100 per resolution element. Data reduction used standard IRAF routines for long-slit spectra. Final one-dimensional integrated spectra were obtained by extracting an aperture covering the core diameter along the slit direction. Since the exposures were trailed over a core diameter perpendicular to the slit, the resulting one-dimensional spectra are representative of the stellar content in the cores of the GCs. The spectra were flux calibrated using observations of flux standards taken throughout the observing run. The one-dimensional integrated spectra had their resolution degraded to match that of the Lick/IDS system, and EWs of absorption lines were measured following the definitions of Worthey et al. (1994) and Worthey & Ottaviani (1997). Consistency with the Lick/IDS index system was achieved by comparing EWs measured in spectra of standard Lick/IDS stars, taken throughout the observing run, with standard values from Worthey et al. (1994).

3. EFFECT OF BLUE HORIZONTAL-BRANCH STARS ON BALMER LINES

In order to highlight the impact of HB morphology on the integrated light, we restrict our analysis to GCs with [Fe/H] $\lesssim -0.5$, because at higher metallicities all Galactic GCs have similar red HBs, therefore not adding much to our discussion. A plot of Hδ_F versus [Fe/H] for this subsample is shown in Figure 1. For most of the GCs, [Fe/H] values were taken from Kraft & Ivans (2003). Those values were supplemented, whenever needed, by data from Carretta & Gratton (1997), Idiart et al. (1997), and Harris (1996). Throughout this Letter, GCs are subdivided in terms of HB morphology, with $x_{\rm HB} = (B - R)/(B + V + R)$, as follows: GCs with *mostly blue* HBs ($x_{\rm HB} > +0.4$), GCs with *mostly red* HBs ($-0.9 < x_{\rm HB} < -0.4$), GCs with *strictly red* HBs ($x_{\rm HB} < -0.9$), and GCs with intermediate HB morphologies ($-0.4 < x_{\rm HB} < +0.4$). Values of $x_{\rm HB}$ were taken from Borkova & Marsakov (2000). In all the figures, a few landmark clusters are highlighted with special symbols (see legend of Fig. 1). Those are 47 Tuc, a metal-rich GC with [Fe/H] ~ -0.8 and a red HB; M67, ∼3.5 Gyr old solar metallicity open cluster (data from Schiavon et al. 2004); NGC 6388 and NGC 6441, the highest metallicity ([Fe/H] ~ -0.6) Galactic GCs known to host BHB stars (Rich et al. 1997); and NGC 5904, a metal-poor GC with [Fe/H] ~ -1.27 (Kraft & Ivans 2003) and whose HB has a sizeable blue extension (Piotto et al. 2002). Our subsample spans a wide range in metallicity and HB morphology; most notably, GCs with $-1.5 \lesssim$ [Fe/H] $\lesssim -0.9$ are strongly affected by HB morphology, in the sense that Hδ_F in strictly blue HB GCs is stronger by ∼1 Å than in those with strictly red HBs at the same [Fe/H].

In Figure 2 we contrast the data with our model predictions for Fe4383 and Balmer lines in single SPs. The Balmer indices were chosen to provide a large baseline and because model predictions were available for them at the time of this analysis. The models used are those by R. P. Schiavon (2004, in preparation; but see Schiavon et al. 2004). For our present purposes, derivation of absolute ages and [Fe/H]'s is not essential, and we focus our discussion on relative spectroscopic ages.

The main issue we address in this Letter is evident in Figure 2: GCs with mostly blue HBs (*asterisks*) have stronger Balmer lines and thus appear younger than GCs with red HBs (*open circles*), even though they are all equally old (e.g., Rosenberg et al. 2002). This effect has been pointed out by many (e.g., Freitas Pacheco & Barbuy 1995; Lee et al. 2000; Beasley et al. 2002; Maraston et al. 2003) and results from the fact that our SP synthesis models do not account for BHB stars, which have strong Balmer lines and mimic a younger age. This is a source of confusion for cluster age estimation based on the EWs of Balmer lines. Furthermore, while the ages of GCs with red HBs do not vary according to different Balmer lines, the same is not true for GCs with blue HBs: their mean ages are ∼3.5 and ∼6 Gyr, as given by Hδ_F and Hβ, respectively. The same effect is also observed in the data for NGC 6388 and NGC 6441 (*open triangles*), whose inferred ages are ∼8 or ∼11 Gyr, according to Hδ_F or Hβ, respectively. In contrast, for M67, which is a cluster of truly intermediate age (∼3.5 Gyr; Schiavon et al. 2004) and whose spectrum is free from the influence of BHB stars, the inferred age is independent of the age indicator. We believe that these effects are caused by the increasing contribution of BHB stars to the integrated GC light at bluer wavelengths, such that Hδ_F is more affected than Hβ. As a result, the GC spectroscopic ages look younger, according to Hδ_F than Hβ.

To verify this hypothesis we computed integrated indices for NGC 5904 directly from its CMD in two different ways: first by taking all the stars into account, and then by removing all the BHB stars in order to assess their effect on absorption-line EWs. This is the most straightforward and model-independent way of assessing the contribution of BHB stars to the integrated GC light. We chose NGC 5904 because its HB is mostly blue and its CMD is indicative of an old age. The colors and magnitudes of NGC 5904 stars were transformed into $T_{\rm eff}$ and log g using the calibrations described in Schiavon et al. (2002a) and assuming [Fe/H] $= -1.27$ (Kraft & Ivans 2003). The re-

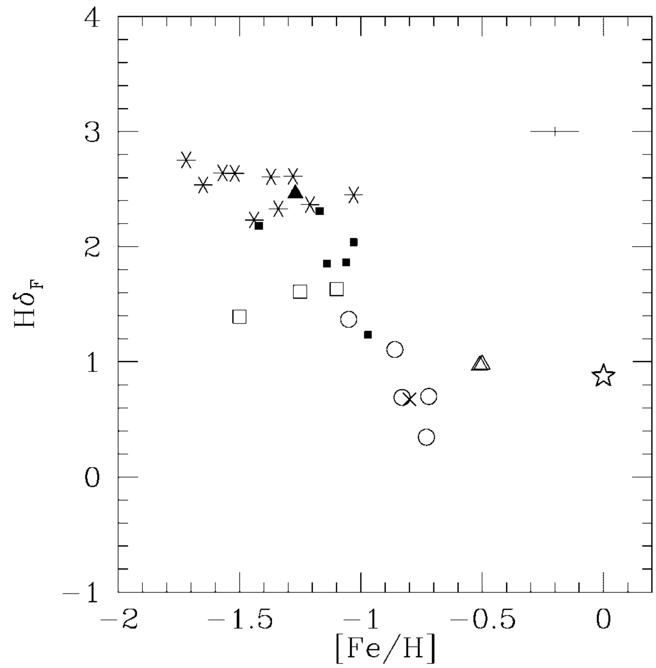

FIG. 1.—Sample of GCs analyzed in this Letter. GCs with mostly blue HBs are depicted as asterisks, open circles represent those with *strictly red* HBs, GCs with *mostly red* HBs are labeled as open squares, and GCs with intermediate HB morphologies are represented by small filled squares. The two open triangles stand for NGC 6388 and NGC 6441, the filled triangle represents NGC 5904, and the mult cross (×) stands for 47 Tuc. The star represents M67. The effect of HB morphology on Hδ can be seen as the ∼1 Å vertical spread for $-1.5 <$ [Fe/H] < -0.9. Here and in all subsequent figures, typical error bars are displayed in the upper right corner.

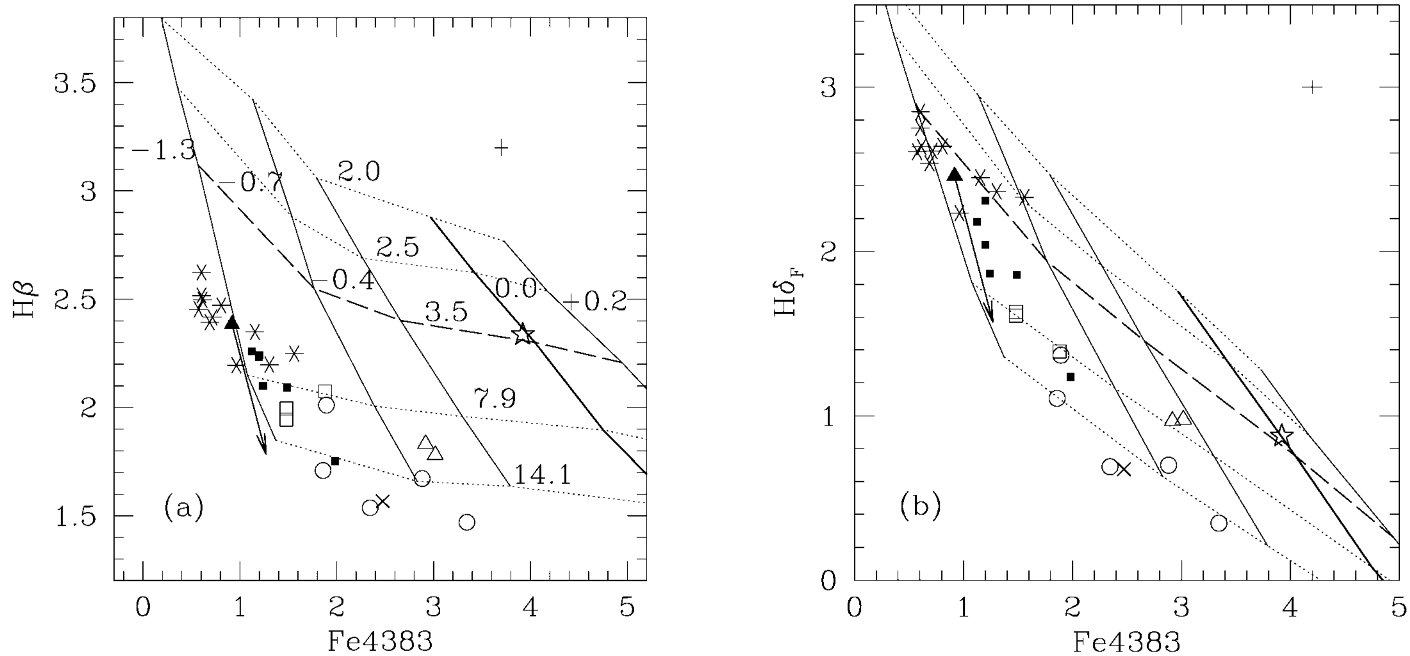

FIG. 2.—Comparison between data and models for single SPs in Balmer vs. Fe4383 plots. Symbols are the same as in Fig. 1. Dotted lines connect same-age models, while isometallicity lines are solid. Model lines are labeled with age and [Fe/H] values in (*a*). As a guide to the eye, the nearly vertical line for [Fe/H] = 0 (*solid*), and the nearly horizontal line for 3.5 Gyr (*dashed*) are both thicker. In both panels, GCs with blue HBs tend to appear younger than those with red HBs, even though they are all old. GCs with blue HBs also look younger, according to Hδ_F (*b*) than according to Hβ. The arrows indicate how the indices for NGC 5904 change when BHB stars are artificially removed.

sulting stellar parameters were used as input to our fitting functions in order to predict line indices for each star in the cluster CMD. The latter are integrated throughout the CMD, with weights based on the photometry and stellar counts. The *BV* photometry, its completeness as a function of *V* magnitude, the distance modulus [$(m-M)_V = 14.46$], and the reddening toward NGC 5904 [$E(B-V) = 0.03$] were taken from Piotto et al. (2002). The result is displayed by arrows in Figure 2 that indicate how index values change when BHB stars are artificially removed from the CMD. The position of the cluster in both plots is shifted toward an old age (∼11–14 Gyr), which corroborates our working hypothesis. Furthermore, the above correction does not alter the agreement of our model predictions with [Fe/H] determinations from spectroscopic analysis of individual stars from NGC 5904 ([Fe/H] ∼ −1.3; Kraft & Ivans 2003).

In summary, we suggest that the different spectroscopic ages inferred from Hβ and Hδ_F are due to the stronger impact of BHB stars on the latter. Below, we use this observation to disentangle the degeneracy between the effects of HB morphology and age on Balmer lines measured in the integrated spectra of GCs.

4. DETECTION OF BLUE HORIZONTAL-BRANCH STARS IN GLOBULAR CLUSTERS

We have identified a distinctive signature of BHB stars in the integrated spectra of Galactic GCs. The obvious implication is that we can devise an indicator that identifies their presence in a given GC solely on the basis of absorption-line EWs. Such an indicator would be most useful for work on distant GCs, for which CMDs cannot be obtained, by providing the means to distinguish truly intermediate-age GCs from old GCs with BHB stars. The best indicator we found is the ratio between Hδ_F and Hβ. Figure 3 displays the main result of this Letter,

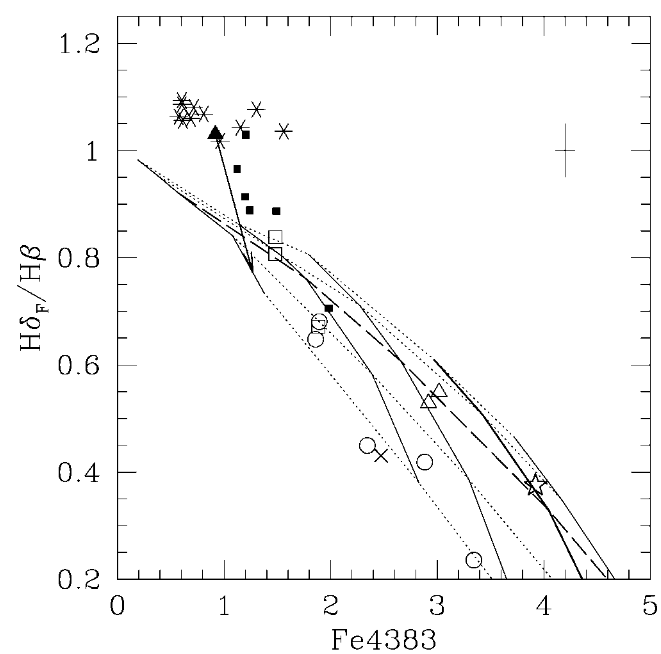

FIG. 3.—Data confronted with the models in the Fe vs. Balmer line ratio plane. Symbols, lines, and arrow have the same meaning as in the previous figures. GCs with blue HBs are greatly displaced from the model locus, indicating ages that are much younger than those found in Fig. 2. In contrast, the ages and [Fe/H]'s for M67 and GCs with strictly red HBs are consistent with those obtained from Fig. 2. The ratio Hδ_F/Hβ is more sensitive to HB morphology than to age, and therefore helps in breaking the degeneracy between the two parameters.

where we plot the data in the $H\delta_F/H\beta$ versus Fe4383 plane, overlaid with our models. It can be seen that GCs with mostly blue HBs are displaced far above the locus occupied by the models, indicating ages substantially younger than ∼2 Gyr, in stark contrast to the ages inferred in Figure 2. In fact, $H\delta_F/H\beta$ is more sensitive to HB morphology than age, given that the separation in $H\delta_F/H\beta$ between GCs with red and blue HBs is about twice that between models for 2 and 14 Gyr single SPs.

GCs with strictly red HBs, such as 47 Tuc, are consistent with the ages and metallicities inferred from Figure 2. As expected, GCs with mostly red or intermediate HBs lie somewhere in between the loci occupied by GCs with extreme HB morphologies. Note that the data for M67, which has a truly intermediate age, are (as in Fig. 2) consistent with its known age and [Fe/H]. We conclude that the ratio $H\delta_F/H\beta$ discriminates between younger clusters and those whose Balmer lines are strengthened by the presence of BHB stars.

The high S/N of our spectra make it relatively easy to detect the influence of the BHB population on the $H\delta_F/H\beta$ index. For instance, for NGC 5904, which has $H\delta_F/H\beta = 1.04 \pm 0.05$ ($1\ \sigma$), the value expected to be consistent with the age estimated from $H\beta$ from Figure 2 (∼ 6 Gyr) would be $H\delta_F/H\beta \sim 0.84$, or $\sim 4\ \sigma$ lower than the measured value. A useful quantity for observers is the minimum S/N needed to distinguish between a GC with BHB stars and a young GC. This was estimated by computing index errors as a function S/N, assuming pure Poisson noise. In the case above, one needs $H\delta_F/H\beta$ measured to better than 0.2, which, for a $2\ \sigma$ detection, requires a S/N of roughly 30–40 $Å^{-1}$ at $\simeq 4100$ Å, a value that can be achieved with reasonable integrations of extragalactic GCs with 8–10 m class telescopes (e.g., Cohen et al. 2003; Larsen et al. 2003; Hempel et al. 2003).

5. FINAL REMARKS

In this Letter we propose a method to detect the signature of BHB stars in the integrated spectra of GCs. If $H\delta_F$, $H\beta$, and an Fe line are measured accurately, one can infer the presence of BHB stars in a given GC if the age indicated by $H\delta_F/H\beta$ is substantially younger than that indicated by $H\beta$. For intermediate-age clusters, the ages indicated by the different indices are the same within the uncertainties. For this method to work, *SP synthesis models employed must predict correct ages and metal abundances for systems with truly intermediate/young ages*. We showed that our models predict the correct age and [Fe/H] for M67. While the case for applying this method to disentangle age from HB morphology seems strong for single-age systems, *it is not clear that it should succeed when applied to galaxies*, where multiple turnoffs due to a complex star formation history cannot, in principle, be distinguished from the combination of an old turnoff with other kinds of warm stars like BHB stars.

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